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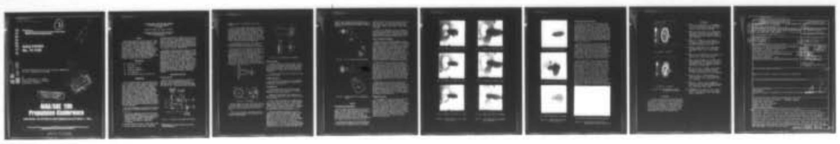

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FLOWFIELD NEAR LIQUID FUEL JETS INJECTED TRANSVERSE TO A HOT SUPERSONIC AIR STREAM

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FLOWFIELD NEAR LIQUID FUEL JETS INJECTED TRANSVERSE TO A HOT SUPERSONIC AIR STREAM*

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Abstract

This paper presents the first results of a study aimed at delineating the processes leading to ignition of liquid fuel jets injected transverse to a hot supersonic air stream. The tests were conducted at Mach 1.8 with a nominal stagnation pressure of 100 psia and stagnation temperatures from 500-1800°F. Kerosene, CS_2 and water were used as the injectants. The observations were in the form of direct, top-view photos, temperature measurements and top-view, infrared Thermographic photos to produce isotherm patterns. Attention was directed, in particular, at the surface layer formed on the wall near the injection port.

Nomenclature

$\dot{m}_j$	Injectant flow rate
M	Mach number
P_o	Stagnation pressure
T_o	Stagnation temperature
T_w	Wall temperature
T_w'	Wall temperature under the liquid layer

Introduction

The flow field produced by the transverse injection of a liquid jet into a supersonic stream is of direct interest in a wide variety of practical systems. One can cite fuel injection in scramjets, local transpiration cooling of re-entry bodies, thrust vector control in rocket nozzles and external burning on projectiles. Previous experimental studies by one of us and previous co-workers and others (Ref. (1) - (10)) have served to document the development of the flow in terms of penetration, break-up and atomization for non-combustible injectants. However, many of the practical applications necessarily involve combustion. Since it is well known from other types of problems that heat release has a dramatic effect upon a flow field, it appears necessary now to proceed to studies directly involving these phenomena.

One feature uncovered in our previous non-burning studies that is potentially important for burning cases is the occurrence of liquid surface layers on the solid surface in the vicinity of the jet itself (Ref. (5) and (6)). Since the flow velocity in the boundary layer immediately above this liquid surface is much lower than that in the vicinity of the jet as it penetrates out, one might expect ignition to occur first near the liquid surface layer due to the resultant increased residence time.

This paper presents the first results of a study aimed directly at delineating the processes of initial ignition in the vicinity of a liquid fuel jet injected transverse to a hot, supersonic air stream. The tests were conducted in a new, specially constructed hot air facility that employs electric resistance heating. The freestream conditions were $M=1.8$, $P_o = 100$ psia and $500 \le T_o \le 1800°F$. Kerosene and CS_2 were injected through a 0.030 in. port perpendicular to the surface. Water injection experiments were run as control cases. The principal observations are top-view direct photographs and infrared photographs with a Thermographic camera to produce colored isotherm pictures. Temperature probing with fine thermocouples was also accomplished.

Experimental Apparatus

Hot Air Facility

The hot air for the supersonic stream was produced by a new, specially designed facility employing a long, thick-walled Inconel 601* tube that was heated by electrical resistance heating (See Fig. No. 1). The electric power was supplied

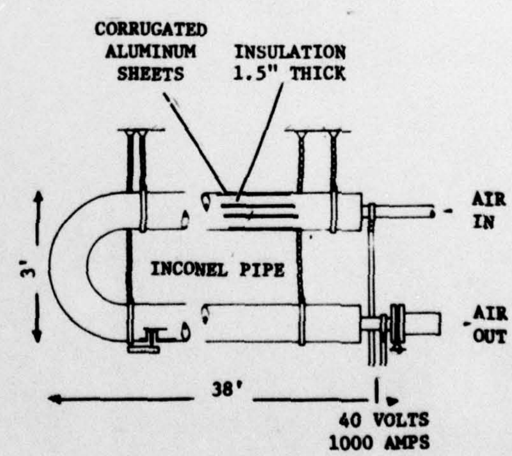


Fig. No. 1 - Details of the Heated Air Facility

* This work was supported by the Air Force Office of Scientific Research with Dr. B. T. Wolfson as Technical Monitor. Several people worked on preliminary studies related to the development of this special test facility. They include J. Bucy, J. Van Overeem, T. Nayfeh and H. deKoningh

† Graduate Research Assistant, Student Member AIAA

†† Professor and Dept. Head, Assoc. Fellow AIAA

* This material was kindly donated by the International Nickel Co.

through a bank of six Plasmatron PS-20 transformers.

The effective, average wall temperature of the tube over its length was determined by a simple thermal expansion gauge. This provided an adequate and rugged means of setting test conditions. From rupture strength considerations at 150 psia, a prudent maximum of 1800°F was selected for the wall temperature. Due to the long length of the tube, the exit air temperature, as measured in the plenum chamber ahead of the nozzle throat, was always very close to the average pipe wall temperature.

It is important to note that this facility produces uncontaminated, dust-free air. This is considered crucial for sensitive ignition studies.

The nozzle used for the present test program is shown in Fig. No. 2. It produced a flow of M = 1.8 at the injection station. The nozzle is fitted with stagnation and static pressure taps, and, perhaps most importantly, two wall temperature measurement devices. The arrangement for both is shown in Fig. No. 3. One instrument is located at the same axial location as the injector, but well away from it around the nozzle. The other is located near the injector in a region that we expected to be covered by the liquid layer based upon our previous work (Ref. (6)).

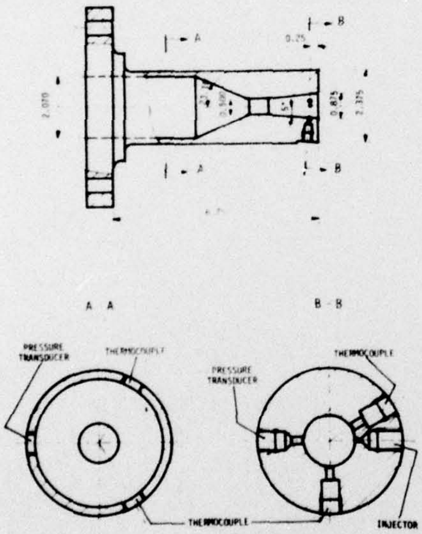


Fig. No. 2 - Test Nozzle

The air supply comes from a Bury VB-3-8, 600 psi compressor through a 70 cubic feet surge tank, a Grove dome pressure regulator operated parallel to a pre-set throttling value and a ball, on-off value.

With all this, accurate, repeatable values of the air stagnation pressure and temperature were conveniently attainable.

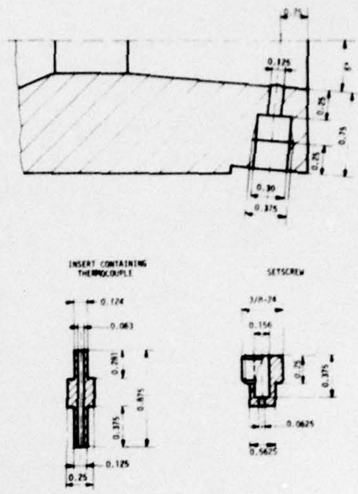


Fig. No. 3 - Wall Temperature Instruments

Injection System

Injectant liquids were driven through the port from a cylinder pressurized with nitrogen. The system involved an elaborate interlocked purge system with fail-safe features. The injectant flow rate was measured by a Ramapo Model V-1/2-SS drag body flow meter.

All tests reported here were conducted at a flow rate of 0.026 #/sec.

Automatic Operation

The tests were run by means of a pre-programmed timer system. This was important in insuring repeatable and safe operation.

Instrumentation

Pressure measurements were made with strain gauge type pressure transducers with the signals recorded on strip chart recorders.

Temperature measurements were obtained using Chromel-Alumel thermocouples again recorded on strip chart recorders.

Direct, top-view photographs were made with a f 2.9, 2.75 in. diam. lens and a 4 x 5 Graflex camera using Polaroid type 57 sheet film. Short duration lighting was provided by single pulses (0.4 μsec duration) from a Strobotac Type 1531-AB. The physical arrangement is sketched in Fig. No. 4. This provided magnification of approximately 2 x 1.

The most informative observations utilized a Thermovision Model 680 Thermographic camera. This camera takes infrared images and processes them internally to produce ten color, isotherm band images of the field of view on a color TV screen. The ΔT for each isotherm band as well as the temperature level of the center of the range are adjustable over a wide range. Our work employs a camera setting of f 14, intensity of 200, and a 6.0% transmission gray filter for high temperature cases. Photographs of the color TV image were taken with

Polaroid type 58 sheet film and a Graflex 4 x 5 camera. The viewing path was the same as that for the direct photos above and the layout is shown in Fig. No. 5.

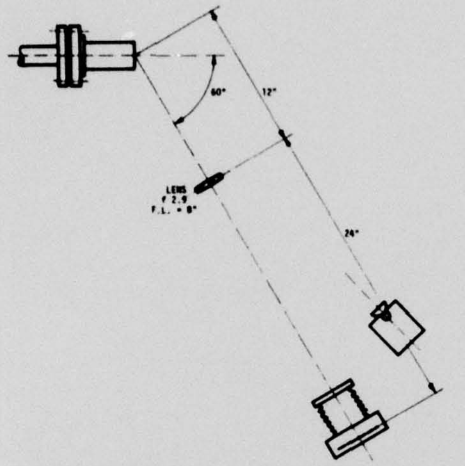


Fig. No. 4 - Optical Layout for Direct Photos

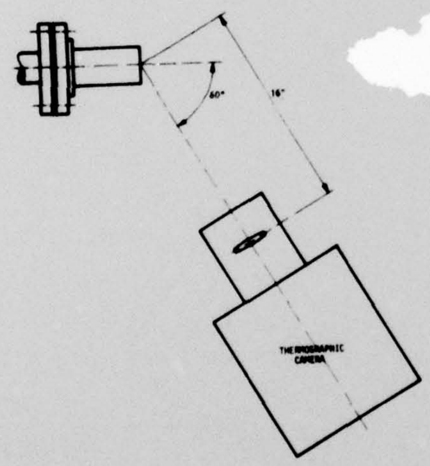


Fig. No. 5 - Optical Layout for Thermographic Photos

Results

Wall Temperature Measurements

The wall temperatures measured by the two instruments - one under the liquid layer and one well removed from it - showed significant and large differences over the whole range of the tests conducted due obviously to local cooling. The direct top-view photos of type to be presented below were used to insure that the first instrument was, indeed, covered by liquid on the surface.

To illustrate the important differences observed, a case with H_2O injection with an air temperature of 1550°F showed a temperature under the liquid layer of 160°F, while that away from the injection port was 530°F. It is also interesting to note that a much lower air temperature of 1000°F produced only a slightly lower value of 150°F under the liquid.

Clearly, wall temperature will be an important parameter in establishing conditions for ignition, but an appropriate value or combination of values must be utilized. We will present further results along with the photographic observations below.

Direct, Top-View Photographs

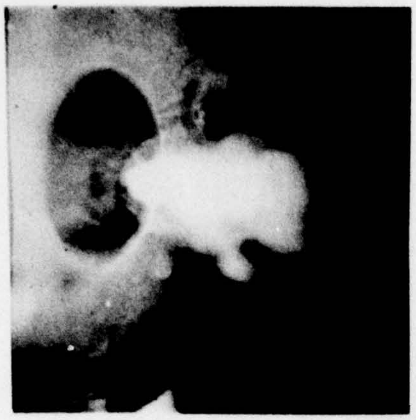
Typical direct, top-view photographs for water injection at various air temperatures from $780 \leq T_o \leq 1600$°F are shown in Fig. No. 6a, b, c. The flow is from left to right. The oblong hole in the middle of the picture is the air nozzle exit, and the white streak going off towards the right is the image of the main liquid jet. To the left and above and below the front of this streak, one can see the liquid surface layer mentioned before. Our tests here produced results completely in accord with the cold flow tests of Ref. (6). As the air temperature is increased, the layer becomes less distinct and apparently thinner, but it is still clearly evident with an air temperature of 1600°F.

Similar photos for CS_2 injection are given in Fig. No. 7a, b, c. These are for the same mass flow rate as those above, but since CS_2 has a specific gravity of 1.26, the volume flow is reduced. Nonetheless, the CS_2 jets are larger when viewed from above than the H_2O jets. This is presumably a result of the lower vapor pressure of CS_2 which produced more rapid spreading. Again, the liquid surface layers are visible at all air temperatures. Due to slight differences in lighting, one can see more evidence of the waves on the liquid surface that were observed before (Ref. (6)) than in Figs. No. 6a, b, c.

While photos of this type are interesting and show many features of the flow, they cannot be reliably used to provide clear evidence of ignition. In Fig. No . 8a, b, and c, we show some photos for kerosene and water injection at an air temperature of 1600°F and kerosene at 1500 and 1600°F. This appears to indicate ignition for the higher temperature case with kerosene, but it is not possible to be certain on this basis alone.

Temperature Probing

In an attempt to obtain more precise supporting data, we conducted an exploratory study with a small (.010 in. diam.) sheathed thermocouple held just above the liquid layer to the side of the main jet body. In one case, this indicated a large difference in temperature between CS_2 and H_2O injection at the same nominal conditions - CS_2 produced the higher temperature. Again, this would seem to indicate ignition. However, we encountered severe problems with frequent thermocouple burn-up. Also, single point probing is tedious and difficult, since one cannot be sure of being in the right place at the right time.

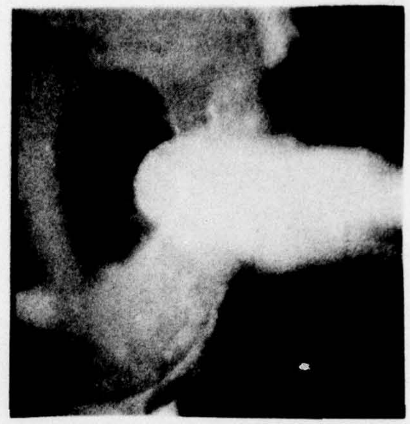


(a) $T_o = 780°F$, $T_w = 320°F$, $T_w' = 145°F$

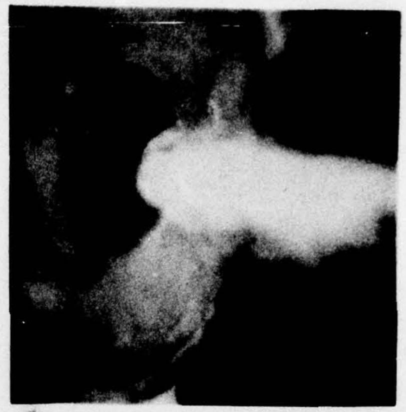
(b) $T_o = 1300°F$, $T_w = 520°F$, $T_w' = 155°F$

(c) $T_o = 1600°F$, $T_w = 600°F$, $T_w' = 160°F$

Fig. No. 6 Direct Photos of H_2O Injection
$\dot{m}_j = 0.026$ #/sec



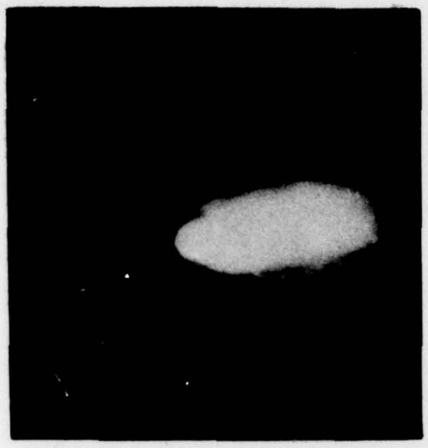
(a) $T_o = 1100°F$, $T_w = 490°F$, $T_w' = 135°F$



(b) $T_o = 1400°F$, $T_w = 510°F$, T_w' 157°F

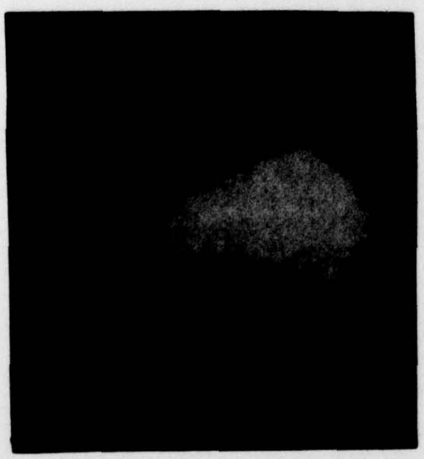
(c) $T_o = 1600°F$, $T_w = 630°F$, $T_w' = 195°F$

Fig. No. 7 Direct Photos of CS_2 Injection
$\dot{m}_j = 0.026$ #/sec



(a) H_2O Injection, T_o = 1600°F

(b) Kerosene Injection, T_o = 1500°F



(c) Kerosene Injection, T_o = 1600°F

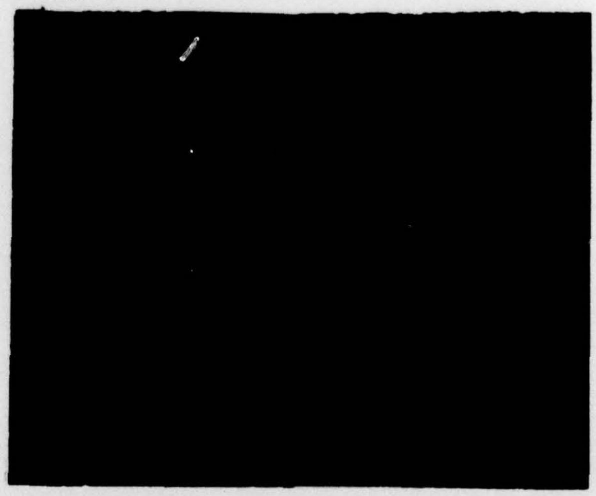
Fig. No. 8 Direct Photos of H_2O and Kerosene Injection

Infrared, Top-View Photographs

As mentioned before, the Thermographic Camera produces 10 color images on a TV screen which we then photographed with Polaroid color film. The resulting pictures are both technically informative and aesthetically beautiful, and it is unfortunate that they cannot be directly reproduced here. Two black and white copies are given in Fig. No. 9a and b. With the use of an opaque projector, the color images were projected on a wall where they could be traced and made into black and white drawings with the colored isotherm bands identified by bands with different symbols. Some typical results are shown in Fig. No. 10a and b.

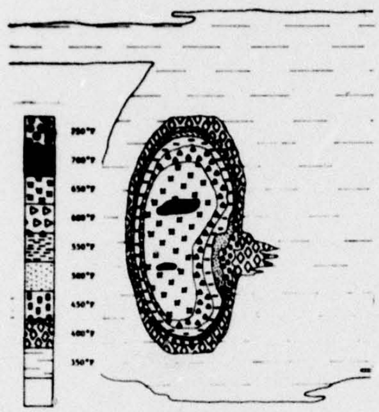
In Figs. No. 9 and 10, the flow is from left to right. The oblong shape in the center is the oblique view of the nozzle exit. The jet comes out of the far nozzle wall in the center and trails off to the right. The main body of the jet produces the jagged protrusion to the right of the vertical oblong. The liquid surface layer is the bulged-in, multi-banded region just to the left of the jet itself. All of this can be much better understood by referring to the direct photos in Figs. No. 6, 7 and 8 which are taken with the same optical path.

These results were obtained using the Thermographic camera outside of its normal calibration range for direct temperature measurements. Also, the effective emissivity of the stainless steel nozzle walls and the liquid surface layer itself are difficult to assess accurately. Lastly, there is the question of the "shape factor" of the surfaces involved. All of these effects conspire to make it difficult to use these photos directly to determine accurate absolute temperature levels in the flow field. All of these matters are under current study, and we expect to be producing results with more reliable precision shortly. For this paper, we have used the admittedly crude technique of correlating the different temperatures with the wall temperatures measured away from the liquid layer. The rest of the variation was assumed linear.

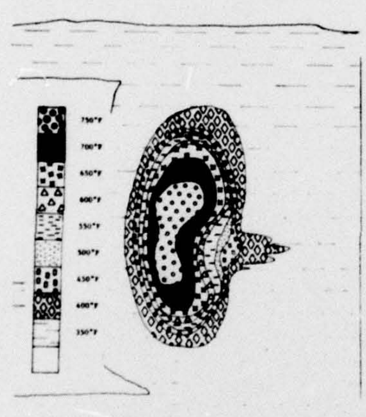


(a) T_w = 590°F, T'_w = 180°F (b) T_w = 615°F, T'_w = 165°F

Fig. No. 9 - Black and White Photos of Color Thermographic Pictures. CS_2, T_o = 1625°F



(a) T_w=590°F T_w'=180°F



(b) T_w=615°F T_w'=165°F

Fig. No. 10 - Line Drawings of Color Thermographic Photographs

Conclusion

Several conclusions can be made on the basis of these first results using a new test technique to study fuel jet ignition. First, an electrically heated, hot air supply of this simple design is very useful and convenient for this type of study. Second, direct photographs do not provide an accurate and reliable indication of ignition. Last, the Thermographic camera has great potential for many kinds of studies in this general area.

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